Economics of diesel fleet replacement by electric mining equipment

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Over the past 10 to 15 years escalating energy costs, especially for diesel fuel, have helped erode the bottom lines of mining companies worldwide. At the same time, there is growing pressure to reduce the exposure of underground workers to diesel emissions. The persistence of these trends would seem to strongly favour electric mining equipment which could eliminate all air quality issues related to diesel engines and also provide a stably priced alternative to diesel equipment. Current conditions create an incentive for examining the economics of electric mining equipment as lower fuel costs and other savings could contribute to lower operating costs. Potential sources of cost savings include reduced ventilation costs, reduced fuel costs, reduced development costs and reduced CO_2 emissions. This paper shows how an engineering model can be developed to examine and compare the economics of diesel and electric equipment. The model examines both operating and capital costs for diesel and electric equipment, as well as the other sources for savings listed above.

Keywords: vent, ventilation, economic, evaluation, electric, diesel, equipment

1. Introduction and background

One of the largest input costs to a mining operation is the energy required to extract and process mineral ores. This demand for energy is typically met by diesel fuel, or electrical grid power.

Historically (starting in the mid 1980's), low and stable energy prices would have made it difficult to justify investing for increased energy efficiency [1]. However, increases in the cost of diesel fuel since the mid 2000's may now allow for a compelling case to be made for transitioning toward more efficient technologies and if possible away from diesel fuel.

The impact of diesel fuel in particular on input costs was identified in reports by industry analysts such as PricewaterhouseCoopers [2] and Ernst & Young [3]. In 2012 the latter specifically identified diesel fuel as the second biggest contributor to cost escalation in the South African mining sector after it had risen at a 15.7% annualized rate since 2007.

In an underground mining operation, the energy intensive extraction process is further exacerbated by the need for ventilating the work environment. In general ventilation is required in order to provide workers and diesel engines a source of fresh air and to dilute and clear away contaminants produced in the mining process. These include the following [4]:

- toxic equipment exhaust gases
- diesel particulate matter (DPM)
- heat
- dust (silica)
- and blasting fumes.

Although there are numerous reasons to ventilate a mine, it is likely that a majority of the costs incurred for ventilation are due in particular to the use of diesel engines underground and the requirement in many mining jurisdictions to supply a given volume of air per bhp operating in the work place.

A 2005 report jointly published by the Canadian Industry Program for Energy Conservation (CIPEC), the Mining Association of Canada (MAC) and Natural Resources Canada (NRCan) looked in detail at how energy is consumed in underground mining operations and found that in a sample of 11 underground operations ventilation was by far the most energy intensive process before milling; accounting for about 50% of the energy consumed and between ⅓ to ⅖ of energy costs before milling. Dollar costs of ventilating the underground operations ranged from \$1.59 to \$4.18 (adjusted to 2014 US dollars) per tonne of ore [5].

In addition to the sustained increase in diesel fuel prices, the industry is also facing more rigorous standards for governing both the quality of the underground work environment and also the allowable levels of pollutants that can be emitted in diesel exhaust. In particular the industry is facing scrutiny of Diesel Particulate Matter (DPM), atmospheric Total Carbon (TC), atmospheric Elemental Carbon (EC) and Nitrogen Dioxide (NO_2). The industry is also facing a possible transition to a new engine standard, i.e. Tier 4, away from the current engine standard Tier 3. However, due to these changing standards and high fuel prices it is difficult to know what new or existing technologies will best serve the industry and provide the lowest costs in years to come.

2. Alternatives to diesel equipment

Over the years, several technologies have been proposed as alternatives to standard diesel equipment in an underground hard rock setting. These at least include the following:

- Tether and trolley-line electric equipment
- Battery powered electric equipment
- Hybrid diesel/electric equipment
- Hydrogen fuel cell equipment

In actuality, the only commercially available alternatives to underground diesel equipment are tether and trolley-line electric equipment, battery powered man carriers and small battery powered scoops and trucks.

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3. The economics & price of diesel fuel

Since the mid 2000's the inflation adjusted cost (US$ 2014) of sweet crude oil on world markets has increased from a ceiling of about $40/bbl to a floor of between $50/bbl and $80/bbl. For a time it even peaked over $140/bbl, a price over 3 and a half times more costly than at any point in the preceding two decades.

Unsurprisingly, movements in world oil prices during this period translated into higher retail prices for diesel fuel and gasoline. For example, between 2003 and 2014 the real retail price of diesel fuel in the US rose from an annual average of $1.92/gal to an annual average of $3.80/gal. This represents a 98% increase in the retail price of diesel fuel, or a 6% annualized increase over the 12 year period.

Conversely, movements in the price of oil were not followed by average market prices for electricity which instead remained relatively stable. During the same 12 year period the real retail price of electricity in the US grew from an annual average of 11.13¢/kW·hr in 2003 to an annual average of 12.39¢/kW·hr in 2014. This represents only an 11% increase in the price of electricity, or a 0.9% annualized increase over the period [1]. Real US retail prices for diesel fuel and electricity from 1999 – 2014 can be seen in Figure 1.

4. Evaluating capital & operating costs

4.1 LHD capital costs

Several recent publications agree that electric LHDs (eLHDs) have higher capital costs than traditional diesel LHDs [6] [7] [8].

The consensus among the sources is that the capital cost of an eLHD is approximately 20% higher than a diesel LHD, however, the differential seen for some smaller pieces of equipment ranged as high as 30% [7]. In addition to the initial premium for eLHDs, Moore notes in his article that a trailer with a diesel generator set could be required to move eLHDs beyond the range of the closest power take off and these could add an additional 10-20% to the purchase cost of an eLHD [6]. The full premium could then range 20to50% above the cost of a diesel LHD.

However, despite the stated premium for eLHDs, two papers suggest it may not be quite so large. For example, a 2014 paper suggests that for loaders of similar bucket capacities, "*capital costs … for diesel and electric machines are similar*" [9]. Furthermore, a 2012 paper develops cost estimation formulae for both types of LHDs, and these do not exhibit the assumed premium for eLHDs when used to calculate costs for machines of equal bucket sizes [10].

For example, equations 1 and 2 were taken from the 2012 paper and they show two exponential relationships developed using single regression analysis (SRA) for estimating the capital cost of both diesel and electric LHDs. The paper indicates they have R^2 values of 0.923 and 0.953 respectively.

In order to compare the cost of diesel and electric LHDs, capital costs were calculated for varying bucket sizes and the difference between Equation 2 and Equation 1 were divided by Equation 1. The results can be seen in Figure 2 which shows that for bucket sizes larger than 3 cubic meters the premium for eLHDs is essentially not observable. Presumably if the premium existed the exponent in Equation 2 would have been much closer to the exponent in Equation 1. Regardless, even though the estimation formulae do not capture a persistent premium for eLHDs, it does not prove a premium doesn't exist. One possibility is that the premium could have just been lost within the margin of error of the estimation formulae.

$$Diesel\ LHD\ Capital\ Cost = 332{,}670x^{0.586} \tag{1}$$

$$eLHD\ Capital\ Cost = 400{,}060x^{0.484} \tag{2}$$

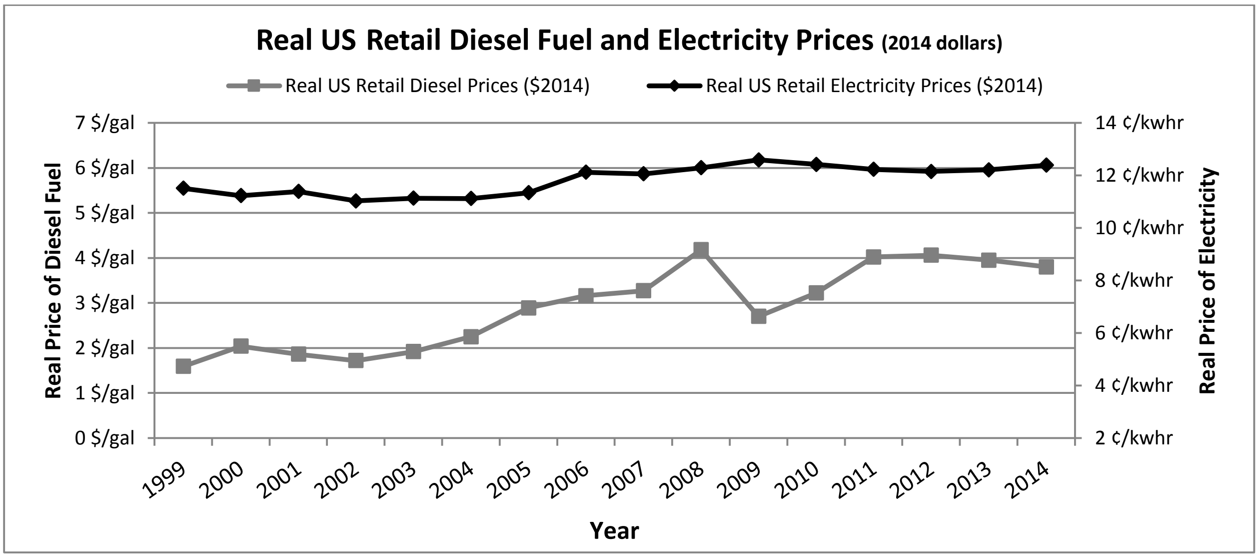

Fig. 1. Real US retail prices for diesel fuel and electricity from 1999 to 2014 in 2014 dollars.

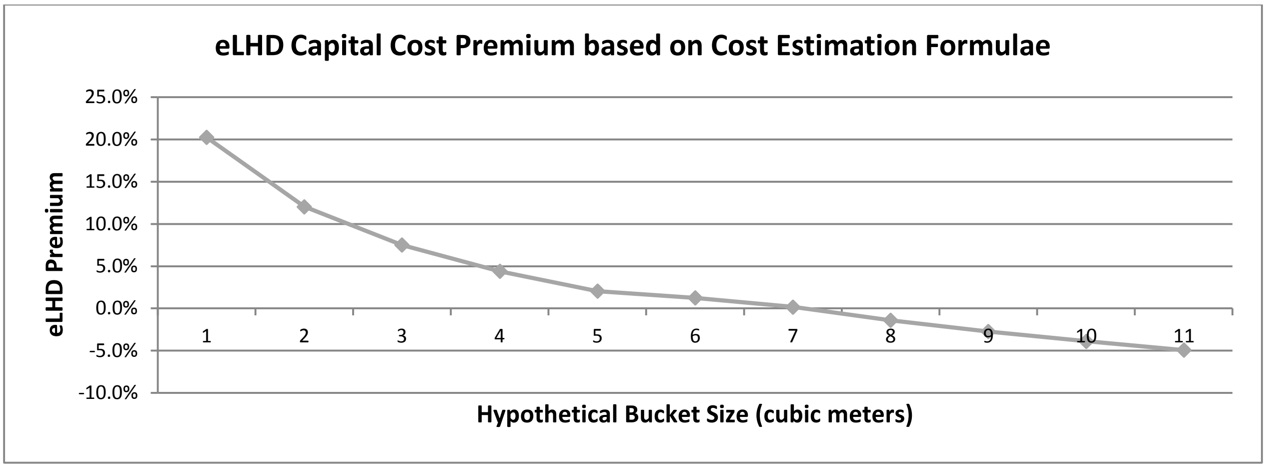

Fig. 2. Diesel and electric cost estimation formulae fail to show a premium for eLHDs.

4.2 LHD operating costs

Operating costs for eLHDs have been reported as being both lower and higher than their diesel counterparts [6] [7] [8] [9]. The reported differences in operating costs are usually attributed to the difference in cost between diesel fuel and electricity prices, and also to how expensive trailing cable maintenance is assumed to be. Although Paraszczak argues that operating costs for eLHDs must be lower under the right operating conditions due to their long and continued use in the Kiruna mine in Sweden [9], he also finds that according to a 2010 estimator's guide that operating costs for eLHDs are 15% higher than diesels.

Conversely, Jacobs finds in a 1993 Australian estimator's guide that maintenance costs for eLHDs are estimated to be approximately 30% lower than diesel LHDs [8]. However, he later inflates the hourly maintenance costs in his analysis by a significant 60% to account for trailing cable replacement. Presumably to match the 15to20% premium reported in the 2010 estimator's guide used by Paraszczak.

Finally, in the 2012 paper by Sayadi et al. [10] it is possible to see how the operating costs (ignoring operator labour) for both diesel LHDs and eLHDs are broken into their component parts, Figure – 3.

The paper doesn't say which total hourly operating cost is higher or lower, however, if we assume that there is no difference in how diesel LHDs and eLHDs consume *Lubricants*, *Tires* and *Wear Parts*, it implies that the total hourly operating cost for eLHDs is lower as this would explain why the three categories appear proportionally larger

If the exercise is completed, the maintenance cost of the eLHD would come out 30% lower, the fuel costs would be approximately 50% lower and the total operating cost would be 30% lower

5. Economic evaluation of equipment using the average annual cost method

In general, the cost of labour should not be distinguished from other operating costs when comparing similar types of equipment. It is also true that maintenance costs are not separate from operating costs. In fact all maintenance costs, including the cost of the labour to complete the maintenance, should be considered a subset of vehicle operating costs.

According to the *Average Annual Cost Method* [11], the average annual cost to run a piece of equipment is equal to the sum of depreciation, interest and operating costs.

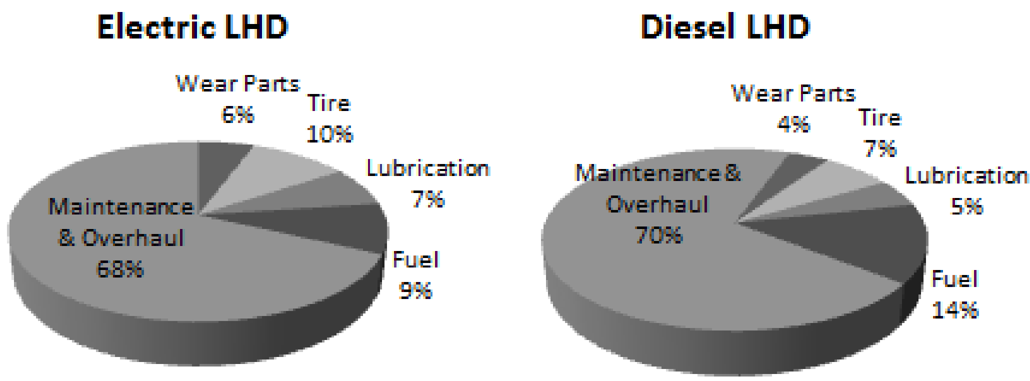

Fig. 3. Components of operating costs from Sayadi et al [10].

For example Equation 1 and its counterpart for operating costs, Equation 3, can be used to approximate an initial capital and operating cost for a 4.8m³ diesel LHD of $833,333 and $100/hr respectively. These estimates can then be combined with the assumptions listed in Table 1 in order to determine the average annual costs for each type of equipment, as seen in Table 2.

$$Diesel\ LHD\ Op.Costs = 36.19x^{0.638} \qquad (3)$$

Table 1. Average annual cost assumptions.

Parameter	Value
LHD Bucket Size	4.8m³
eLHD Cap. Ex. Premium	20%
eLHD Op. Ex. Premium	15%
Operating Hours per Year	6,000
Operator Salary per Year	$100,000
Number of Operators	4
Service Life	4yr
Depreciation per Year	20%
Salvage Value	20%
Cost of Capital	8%

As can be seen from the average annual costs for each piece of equipment, even though eLHDs are assumed to cost 20% more than diesels to buy and 15% more than diesels to run (outside of labour costs), they are only 11% more costly to run each year on an all in basis.

Assuming the operating costs of electric equipment can vary based on their operating conditions, it is possible to use a range of operating costs to see how they impact the annual average cost.

Table 2. Average annual cost calculations.

Parameter	Diesel	Electric
Capital Cost	$0.83 M	$1.00 M
Salvage Value	$0.17 M	$0.20 M
Avg. Annual Investment	$0.50 M	$0.60 M
Avg. Annual Interest	$0.04 M	$0.05 M
Op. Ex. Less Labour	$0.60 M	$0.69 M
Annual Labour	$0.40 M	$0.40 M
Annual Depreciation	$0.17 M	$0.20 M
Average Annual Cost	**$1.21 M**	**$1.34 M**

Accordingly, Figure 4 shows the sensitivity of eLHD average annual costs to operating costs. It can be seen that despite an assumed 20% higher capital cost, if operating costs are assumed to be equal to a diesel LHD then the average annual cost of an eLHD is only 3% higher than a diesel LHD. As operating costs are assumed to be lower than diesel LHDs, it can be seen that eLHDs become less costly overall, again, despite the higher capital cost.

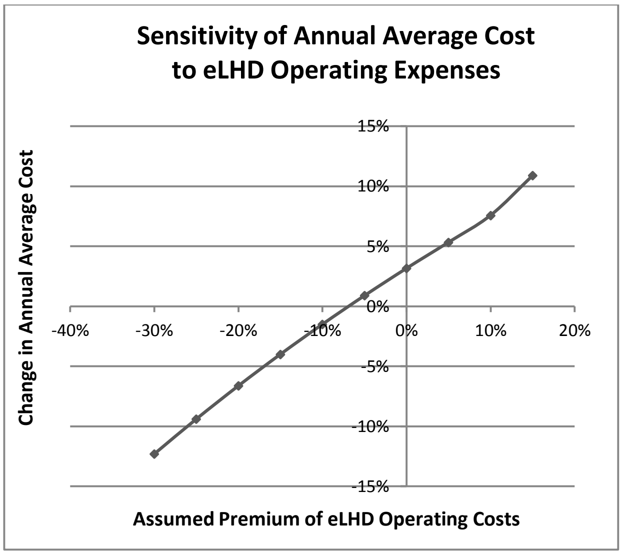

Fig. 4. Sensitivity of eLHD avg. annual cost to Op. Ex.

6. Estimating airflow requirements for electric equipment

Two recent papers address ventilation requirements for the dissipation of heat in an underground mine. The first addresses the heat produced by diesel equipment [4] and the other addresses the heat produced by electric equipment [12]. The first paper estimates the flow rate necessary to prevent the air temperature from increasing by more than 20°C for a specific engine size and its estimated consumption of diesel fuel. It found that a flow rate of 0.075m³/s per kW was necessary to prevent a temperature increase greater than 20°C. Making a basic assumption that electric motors produce $^{1}/_{3}$ the heat for an equal amount of work [6] [9], perhaps this would suggest a flow rate of 0.025m³/s per kW for electric equipment.

The second paper assumed that the heat a piece of electric equipment contributed to the work environment was equivalent to its engine rating. It also assumed that an electric equipment fleet could be approximated by assuming vehicle motors were 70% as powerful as their diesel alternatives. It then used modelling software to determine how much airflow was required to prevent the deepest parts of various mine models from exceeding 30°C.

It was found that in a deep mine with little heat added from the host rock a flow rate of 0.04m³/s per kW could maintain the desired temperature. In a shallow mine, the necessary flow rate was found to be 0.03m³/s per kW.

Both of these approaches are helpful as they demonstrate the magnitude of air flow that could be expected to adequately supply electric equipment. However, it is likely that additional factors should be considered in order to determine how much airflows can be reduced in a mine fully benefitting from electric equipment.

For example, the following should also be considered:

- The above flows are calculated assuming each piece of equipment is operating at full load 100% of the time. In an operating mine, this is unlikely (even in the case of electric equipment, it should be considered how a changing load affects the Power Factors of the machine's motors).
- Adjustments were not made to auxiliary fans, and reducing aux. fan size could result in significant power savings (and also reduce heat loading underground).
- The ability to effectively exhaust blasting fumes in an acceptable amount of time should also be considered when discussing the lower limit to reducing airflows.

In order to determine ***total*** mine flowrates for electric equipment, it is proposed that the following steps be followed:

1) Determine the average heat loading of the equipment fleet, auxiliary fans and other sources during operation.
2) Consideration should then be given to adjusting total flow requirements according to estimations (or measurements) of equipment utilization rates.

For ***drift*** airflow requirements, the following steps are proposed:

1) Consider reducing the expected max heat loading (determined from the max number of kWs that will be operating in the heading at one time) by an engine/motor load factor.
2) Ensure auxiliary fans will provide a sufficient volume of air to
    a. maintain an adequate flow velocity for working in the drift and
    b. allow the drift to be quickly cleared of blasting fumes.

In order to estimate heat loading in a drift consider that a 300kW LHD on average throughout the shift might have an engine load factor of just over 50%. In this case, fuel consumption would be approximately 50L/hr as opposed to the ~90L/hr [4] that would be consumed under full load. This estimate might be considered reasonable as it happens to be proportional to the 40L/hr Jacobs used for a 256kW LHD in his cost/benefit analysis [8].

In this case it could be argued that the diesel LHD on average requires 0.0375m^3/s per kW to dissipate heat. Assuming that on average an eLHD would do the same amount of mechanical work in a shift as an LHD and that each has a thermal efficiency of 35% and 90% respectively, then the 0.0375m^3/s per kW can be factored by 0.4 (0.35/0.90 = 0.39) which results in a required airflow of 0.015m^3/s per kW. To account for peak engine loading and to provide a factor of safety, this number could even be rounded up to 0.018, or 0.020 m^3/s per kW (20-30%). This represents a 65% lower flowrate than the current regulation in Ontario.

7. Framework for evaluating total potential operational savings

7.1 Determining drift and level requirements

Due to issues that would arise in situations where lower airflow requirements would result in very low flow levels in a drift, the clearest example of savings on a local level are where flows would change from high to moderate. A good example would therefore be a level or drift where haul truck and LHD operation overlap (i.e. both operate at the same time).

For example, a 30t diesel haul truck with a 305 kW (410 hp) engine and a 6yd diesel LHD with a 200 kW (270 hp) engine typically would require 32 m^3/s (68 kcfm) at 0.063 m^3/s per kW. Assuming 25% leakage, a fan should supply 40 m^3/s (85 kcfm).

Assuming these pieces of equipment were replaced by a 35t trolley-electric haul truck with a 72 kW diesel engine (400 kW main drive) and a 6yd eLHD with a 110 kW drive, then airflow requirements would be 4.5 m^3/s for the haul truck at 0.063 m^3/s per kW diesel and 2.2 m^3/s for the eLHD at 0.02 m^3/s per kW electric. The combined supply is then 6.7 m^3/s (14 kcfm) or 8.5 m^3/s (18 kcfm) with 25% leakage. Accordingly the velocity of air in a 4.5mWx4.5mH drift would drop significantly, but a final velocity of ~0.4m/s would not be unmanageable.

Table 3. Size reduction of auxiliary fans.

Parameter	Q_1	Q_2	Q_3
Flow (cfm)	85,000	18,000	18,000
Duct Length (ft)	492	492	492
Duct k-factor	25	25	25
Duct Diameter (in)	60	60	36
Hs (in w.g.)	3.55	0.16	2.05
Fan Diameter (in)	48	48	36
Hv (in w.g.)	2.85	0.13	0.40
Ht	6.40	0.29	2.45
rpm	1780	n/a	1780
Motor hp	150	n/a	25
Blade ∠	28°	n/a	20.5°

By approximating a suitable fan according to the parameters in Table 3, it can be seen a 48” 150 hp fan would be required to supply 40 m^3/s (85 kcfm) whereas only a 36” 25 hp fan can supply 8.5 m^3/s (18 kcfm).

7.2 Determining total mine airflow

A base case scenario was imagined for a diesel fleet at a 3,000 tpd hard rock operation. Estimates for the total installed diesel power of different equipment types and their Utilization were combined in order to determine how much ventilation would be required for each type of equipment underground. Table 4 shows the original estimates for diesel power utilized in the work place and the air required for ventilation at 0.063m^3/s per kW.

Table 4. Estimating total mine airflows.

Equipment Type	Utilized kWs	Base Q m^3/s (kcfm)	New Q m^3/s (kcfm)
Man Carriers	1,200	75 (160)	20 (40)
LHDs	1,350	85 (180)	15 (30)
Haul Trucks	3,000	190 (400)	80 (170)
Jumbos/Bolters	160	10 (20)	10 (20)
SLs/ANFO Loaders	320	20 (40)	20 (40)
Boom Trucks/Misc.	320	20 (40)	20 (40)
Auxiliary Fans		n/a	10 (30)
Total	6,350	400 (850)	175 (370)

To determine how the flow rate would change with electric equipment, the Utilized kWs were factored by the differences in engine/motor power seen in the previous sub-section and then multiplied by the new rate of $0.02m^3/s$ per kW. So, for example the 3,000 Utilized kWs assumed for Haul Trucks was multiplied by (400/300) to get 4,000 Utilized kWs and then $0.02m^3/s$ per kW to get $80m^3/s$. eMan Carriers were assumed to have a motor power of 70 kW compared to 100 kW diesel Man Carriers. As seen in Table 4, flows decreased by ~60%.

7.3 Determining fuel savings

In order to calculate fuel use, assumptions (or measurements) must be made for the length of time equipment operates on average and how much fuel is consumed on average while it is operating.

For example the Effective Utilization of equipment could be multiplied by the shift length to determine how many hours on average that equipment operates each day. Then, from the on board computer (or some other form of data collection) the fuel consumption can be determined in liters or gallons per hour. The ratio of the actual fuel consumption to the maximum fuel consumption at full engine load could be considered the average engine load factor. For the purposes of demonstrating how fuel savings could be calculated, the following can be assumed:

- Diesel Engine Avg. Load Factor: 0.55
- Electric Motor Avg. Load Factor: 0.80
- Motor kW ≈ 70% of Diesel Engine kW

These values could be applied to the LHD Utilized kWs from Table 4, for example, to calculate that both the LHDs (1,350 kW * 0.55 = 750 kW) and eLHDs (1,350 * 0.7 * 0.8 = 750 kW) complete roughly the same amount of work per hour of operation. However, assuming fuel consumption of 0.3 L/ kW·hr [4], the diesel engines will consume 225L of fuel per hour, or approximately $180 in fuel at $0.8/L. Whereas electrical power at $0.07/ kW·hr would cost only $53 for the same hour.

7.4 Direct cost savings

7.4.1 Main fan savings

Assuming there are 2 main fans for this mine and each supplies 200 m^3/s at a total pressure set point of 3kPa (12"w.g.) and fan efficiencies of 83%, then using Equation 4 (metric) the power of the main fans can be calculated at 725kW each.

$$P_{fan} = \frac{H_T \cdot Q}{\eta} \tag{4}$$

Assuming no changes to the rest of the vent system, and fan diameters of 112", Equations 5 and 6 can be used to determine that a reduction in the flow rate to $175m^3/s$ would result in a system total pressure of (0.57 kPa + 0.11 kPa) 0.68 kPa, a roughly 75% decrease. Again, using Equation 4 and assuming similar fan efficiencies, it is possible to see that the new system pressure would imply fan powers of 72kW each, a roughly 90% reduction in power.

$$H_{s_2} = \frac{H_{s_1} \cdot Q_2^2}{Q_1^2} \tag{5}$$

$$H_V = 0.6007 \cdot V^2 \tag{6}$$

Assuming the main fans ran 24 hours a day 360 days a year, at $0.07/kW·hr the difference in operating cost would be $790,000 per year.

7.4.2 Auxiliary fan savings

A similar analysis can be made for the local ventilation on a working level like the example described in Section 7.1. Assuming power costs of $0.07/kW·hr and the auxiliary fan has a load factor of 0.85, a utilization of 0.75 and operates 365 days a year, it is possible to calculate that the 150hp fan would cost $43,700 in power per year, whereas the 25hp fan would cost only $7,300 per year . If 40 similar fan installations existed in an underground mine, the difference in power costs would be $1.46M per year. Overall power requirements for the mine grid would drop by 3.7MW.

7.4.3 Fuel savings

Assuming that the same factors listed in Section 7.3 were applied to all of the equipment in Table 4, then the total fuel bill would be $2.75M per year for diesel equipment versus only $0.82M for electric. The difference in fuel costs would work out to $1.93M each year.

8. Evaluation of potential economic benefits of electric equipment

Considering only the sources for cost savings already discussed it can be seen in Table 5 that these would total to $4.2M per year. However, there are additional sources of savings which could further reduce annual operating costs and these include the following:

- Mine air heating and/or cooling
- Smaller headings and raises
- And possibly in the future CO_2 credits

For example, assuming that the operation in question completes about 7,000m (20m/day * 350 days) of 5.5mWx5.5mH development per year, reducing the size of the duct used for ventilation from 60” to 36” in diameter could reduce the volume of material in each meter of development by 2.75 cubic meters (0.5m*5.5m). Assuming development costs of $145 per cubic meter, over the course of the year development costs would be reduced by $2.79M.

It is also possible to anticipate how a possible carbon credit or tax would add to the advantages offered by electric equipment. Assuming that each liter of diesel fuel emits 0.00269t of CO_2 and each MW·hr of electricity emits 0.133t of CO_2 (Ontario), it is possible to calculate that replacing diesel fuel reduces CO_2 emissions by approximately 7,750t per year and that reducing the power consumed by ventilation would further reduce CO_2 emissions by 4,275t per year. Assuming a similar price for carbon emissions as in the EU (€20/t ≈ $27/t), these reductions would amount to an additional saving $0.3M per year.

Table 5. Potential Economic Benefits of eEquipment.

Operating Costs	Savings
Fuel	$1.9M
Main Fan Power	$0.8M
Aux. Fan Power	$1.5M
Sub Total	$4.2M
Reduced Propane Use	$0.5M
Development	$2.8M
Total Carbon Credits	$0.3M
Total Potential Savings	$7.8M

If these savings were realized by a gold mine which produced 200,000 oz of gold a year with *Cash Costs* of 700/oz, these cost savings would reduce its *Cash Costs* by ~$39/oz which would equate to a ~5.6% reduction in operating costs. Alternatively, assuming an *All In Sustaining Cost* (AISC) of $900/oz the savings would equate to a 4.3% reduction in operating cost.

As world oil prices have proven volatile, it is possible to consider how the reduction in *Cash Costs* will change as the price of diesel fuel changes. In Figure 5 it can be seen that with diesel prices ranging from 60 to 120 cents per liter the total potential reduction in *Cash Costs* ranges from 5.1% to 6.6%.

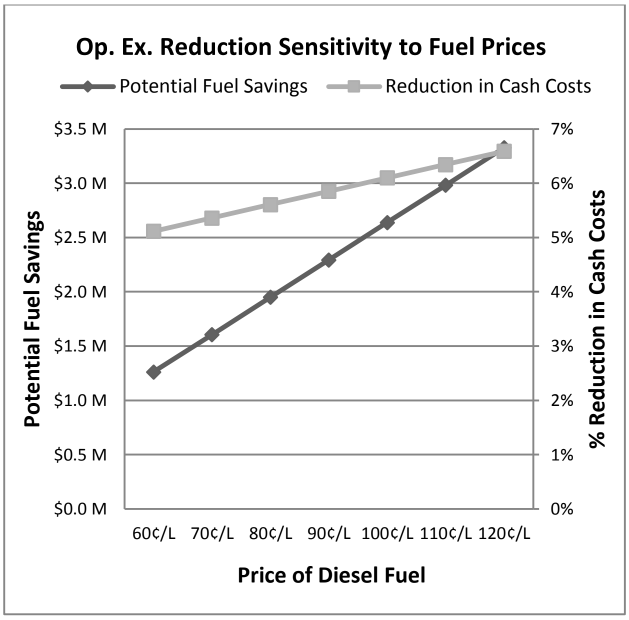

Figure 5. Op. Ex. Sensitivity to Fuel Price.

9. Summary, conclusions and future work

It is possible to see that the price of diesel fuel in particular provides a significant incentive to find alternative sources of power. However, it is also possible to see that there are a number of other factors which contribute to a mine’s operating costs which could be reduced by transitioning away from traditional diesel equipment. In particular, the reduction in the power consumed not only by the main fans, but also by auxiliary fans and also the amount of development that currently needs to be done to support existing ventilation practices all contribute significantly to operating costs. Using reasonable approximations, this paper showed operating costs could be reduced on the order of 5% by optimizing power use and ventilation in underground hard rock mines. However, following a similar methodology with more refined numbers, perhaps using a real world case study, might reveal even more potential for the reduction of costs.

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